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TECHNICAL REPORT 1849
January 2001

Tactical Routing Using Two-Dimensional and Three-Dimensional Views of Terrain

M. St. John
H. S. Smallman
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**Pacific Science and Engineering
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ADMINISTRATIVE INFORMATION

The work in this report was performed for the Collaborative Technologies Project Team (D44210) of the Simulation and Human System Technology Division (D44) of the Command and Control Department (D40) of SSC San Diego by Pacific Science and Engineering Group, Inc., under contract number N66001-99-D-0050. Funding was provided by the Office of Naval Research (ONR), Human Systems Department (Cognitive, Neural, and BioMolecular Science and Technology Division), under program element 0602233N. The ONR program officer was Dr. Helen Gigley. This report covers work from October 1998 to June 2000.

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EXECUTIVE SUMMARY

Consoles for military and civilian occupations such as air warfare, command and control, air traffic control, piloting, and meteorological forecasting will be capable of displaying three-dimensional (3-D) perspective views. The question is when and how to use 3-D views effectively. This report discusses the results of two experiments where participants placed objects on a terrain map in 3-D or two-dimensions (2-D). In these experiments, we showed participants a terrain map that contained two fixed antennas (a source and terminal), several enemy unit locations, and a set of antennas to be placed on the map to establish line-of-sight communications. The task was to create a chain of antennas across the map to connect the source and terminal antennas. The antennas had to be within line of sight of each other while remaining concealed from the enemy units. We found the following:

- Antenna placement was performed better with a 2-D view than a 3-D view.
- Antenna placement was performed best when participants were provided both a 2-D and 3-D view.
- Initial planning of the antenna route was performed better with a 3-D view than a 2-D view.

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INTRODUCTION

Objects and scenes displayed on a flat screen from a 30- to 60-degree perspective viewing angle can convey three-dimensional (3-D) structure and shape. Three-dimensional perspective displays are increasingly used in military and civilian occupations such as air warfare, command and control, air traffic control, piloting, and meteorological forecasting. However, the displays are not effective for all tasks. Comparisons between 2-D (top-down, side) and 3-D (perspective) displays in the literature on various tasks have provided mixed results.¹ Several factors have been proposed to account for the differences (e.g., Haskell and Wickens, 1993; Van Orden and Broyles, 2000; and Wickens and Prevelt, 1995). In an attempt to identify and evaluate the factors that are important to the effectiveness of the viewing angle, we developed a series of experimental tasks using simple block stimuli (figure 1, left) viewed on a non-stereo display. We found that 3-D views were superior for tasks that required understanding the shapes of the blocks, but that 2-D views were superior for tasks that required judging the precise relative position between the blocks and another object (a ball) in the scene (St. John and Cowen, 1999). In these experiments, the 3-D view was from 30 degrees with shading and the 2-D views were from the top, the front, and the side.

We then extended these findings to more complex and naturalistic terrain stimuli. We showed participants a 7- by 9-mile piece of terrain in either 2-D or 3-D (figure 1, right) and asked them to perform tasks that required either shape understanding or relative position judgment. We again found that 3-D views were superior for the shape understanding tasks and 2-D views were superior for relative position judgment tasks (St. John, Oonk, and Cowen, 2000; St. John, Smallman, Oonk, and Cowen, 2000). In these experiments, the 3-D view was from 45 degrees with shading and the 2-D view was a topographic map with color-coded contour lines.

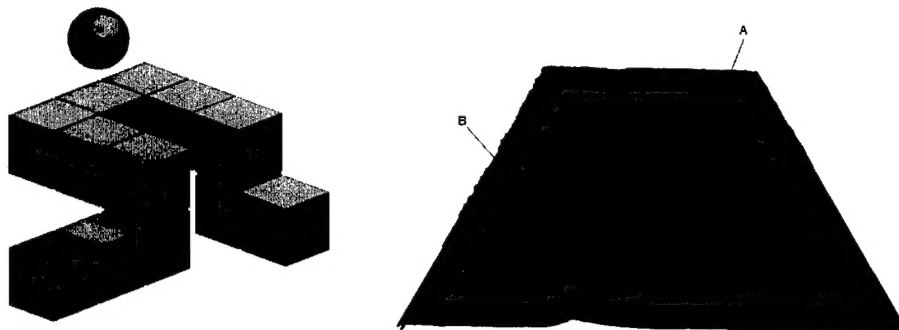


Figure 1. Simple block stimuli and terrain stimuli (3-D perspective views).

¹ Many studies have found benefits for 3-D perspective over 2-D (Bemis, Leeds, and Winer, 1988; Ellis, McGreevy, and Hitchcock, 1987; Hickox and Wickens, 1999; Liter, Tjan, Bulthoff, and Kohnen, 1997; Naikar, Skinner, Leung, and Pearce, 1998). Other studies have found rough parity or different results on different measures or tasks (Andre, Wickens, Moorman, and Boschelli, 1991; Baumann, Blanksteen, and Dennehy, 1997; Burnett and Barfield, 1991; Haskell and Wickens, 1993; Van Breda and Veltman, 1998; Wickens, Liang, Prevelt, and Olmos, 1996; Wickens and Prevelt, 1995), and still other studies have found 2-D superior to 3-D (Boyer, Campbell, May, Merwin, and Wickens, 1995; Boyer and Wickens, 1994; O'Brien and Wickens, 1997; Wickens, Campbell, Liang, and Merwin, 1995; Wickens and May, 1994; Wickens, Miller, and Tham, 1996).

This report includes a follow-on study that extended our findings to a real-world task. This task, called the "Antenna Placement Task," involved route planning. We showed participants a terrain map in 2-D or 3-D that contained two fixed antennas (a source and terminal), several enemy unit locations, and a set of antennas to be placed on the map to establish line-of-sight communications. The task was to create a chain of antennas across the map to connect the source and terminal antennas. The antennas had to be within line of sight of each other while remaining concealed from enemy units.

The task was somewhat difficult. It required placing antennas in precise locations and considering constraints concerning the shape of the terrain and multiple lines of sight. The task required a good understanding of the terrain to find promising routes and to hide antennas. It also required estimating the relative heights and distances among antennas, the enemy units, and the terrain.

We expected that some aspects of the Antenna Placement Task would be performed better in 2-D while other aspects would be performed better in 3-D. The Antenna Placement Task provided us an opportunity to investigate how to combine multiple views to help performance. We were interested in how 2-D and 3-D views would influence performance on the Antenna Placement Task, which aspects of the task might benefit more from either type of view, and how multiple views could be combined to help overall performance.

THE GEOMETRY OF 2-D AND 3-D VIEWS

Before continuing, it is useful to understand the basic geometric and functional differences between 2-D views and 3-D views (Sedgwick, 1986). One reason why 3-D views are good for understanding the general shape of objects and the layout of a scene is that all three spatial dimensions of an object can be seen within a single integrated view (Wickens and Carswell, 1995). With a single integrated view, the user does not need to switch among and integrate information from separate 2-D views to obtain an understanding of the three-dimensional shape of an object or scene. Another reason why 3-D views are good for understanding shape is that natural cues to depth, such as shading, relative size, and texture, can be readily added to an image. Adding these cues can increase the salience of depth in the scene and thereby enhance the sense of three-dimensional shape. Stereo and motion can also be used to aid the perception of depth (Smallman, Schiller, and Cowen, 2001), though they are less commonly used.

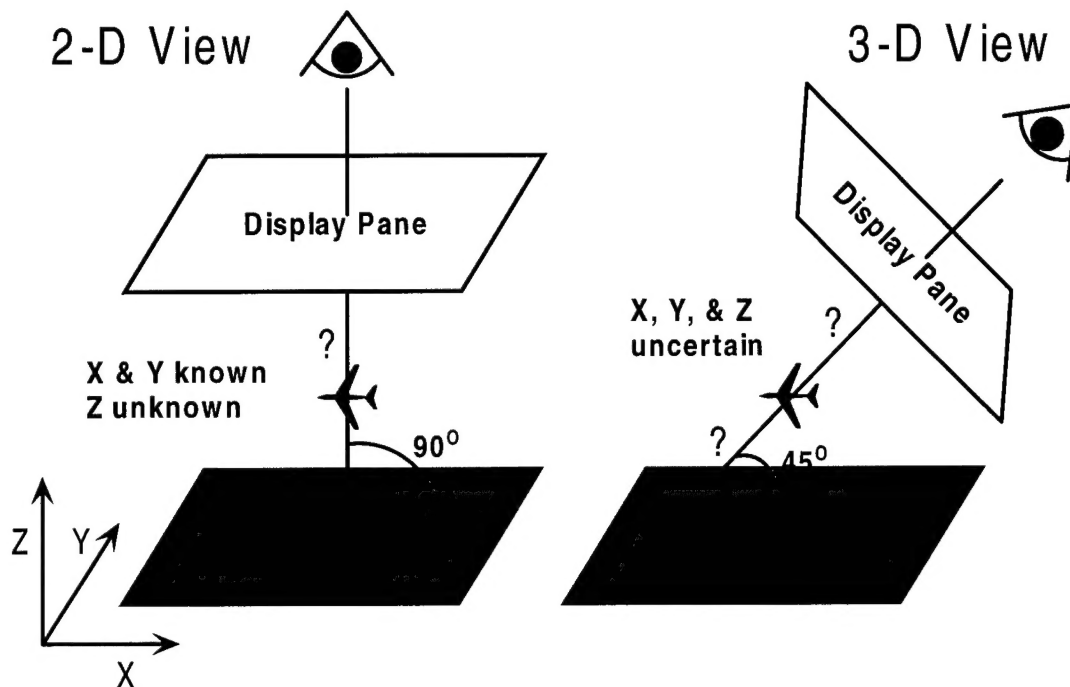


Figure 2. Line-of-sight ambiguity makes the location of the aircraft uncertain in different ways, depending on the viewing angle.

One problem for 2-D and 3-D views is that information along the line of sight from the observer into the scene cannot be represented. The reason is that all of the information along a line of sight between the object in the displayed world and the viewer must be represented by the same pixel in a display. In a 2-D top-down or “plan” view, the x and y dimensions are represented faithfully, while the z dimension is lost entirely (figure 2). The x and y dimensions are scaled down in the plan view. What is meant by “represented faithfully” is that this scaling is a linear transformation that preserves angles and relative distances in the x-y ground plane so that, for example, parallel lines remain parallel.

In the 3-D view, all three spatial dimensions are represented, but the line-of-sight ambiguity remains. Instead of losing one dimension entirely, all three dimensions are foreshortened. Figure 1 (left), where the location of the ball cannot be determined, shows the effect of this ambiguity. Is the ball floating high up over the front cubes or low down over the rear cubes?

A further problem for 3-D views is distortion in the representation of distances and angles. Some distortions result from foreshortening, which increases as the viewing angle drops from directly top-down to ground level. This distortion can cause the sides of a square to appear shortened and the right angles to appear acute or obtuse (figure 2). Other distortions result from perspective projection, which causes distances in the x and z dimensions to scale linearly (linear perspective), but distances in the y dimension to scale nonlinearly. Parallel lines appear to converge toward the vanishing point (figure 1, left). Perspective projection is a cue to depth, but it distorts distances and angles. It makes depth more salient in an image, but makes precise measurements more difficult.

EXPERIMENT 1: ANTENNA PLACEMENT

Analysis of the geometry of 2-D and 3-D views, and our previous results, suggest several predictions for the Antenna Placement Task. The shape understanding capabilities of 3-D views should help participants understand the terrain and find promising paths for line-of-sight communications. For instance, 3-D views should make it easier for participants to find canyons to hide antennas while crossing a mountain range. Placing antennas too deep in a canyon may keep them out of sight of the enemy, but it can also keep them out of sight of each other. Antenna placement on hilltops helps create line-of-sight communication, but leaves the antennas exposed to enemy detection. Finding intermediary positions, in line of sight of each other and just out of view of the enemy, may prove difficult and time-consuming.

It is not clear which type of view will prove better for making these precision judgments. In previous work (St. John, Oonk, and Cowen, 2000), we used line-of-sight judgments as a shape understanding task and found that 3-D views were superior. Participants viewed a terrain segment in either a 2-D top-down topographic view or a 3-D perspective view and judged whether or not there was a line of sight between two points on the terrain. This task appeared to require only a very general gestalt understanding of the terrain—whether a large mountain or range of hills was obstructing the line-of-sight view. In contrast, placing antennas on a map to create an unbroken chain of line-of-sight communications while keeping them out of sight of enemy units may require far more precise judgments. If so, 2-D views may be more useful than 3-D views for making these precise judgments because of their faithful representation of space.

In summary, a 3-D view will most likely be more useful for finding promising general line-of-sight routes while a 2-D view may be more useful for judging precise lines of sight. If this task-by-display interaction holds, then a further issue is how to combine both types of views to provide the right display at the right time. Our previous findings imply that combining 2-D and 3-D views may prove optimal for use in operational military settings. We proposed a concept called “Orient and Operate.” Users *orient* to the layout of a scene using a 3-D view, but then switch to 2-D views to interact with and *operate* on the scene. We begin to address this issue here by creating a condition in which the 2-D and 3-D views are displayed side by side on separate monitors. The participant is free to look at either view of the terrain. There are many issues involved in creating the “Orient and Operate” design model. Our side-by-side configuration represents our first test of this concept.

METHOD

Participants

The participants were 48 students from local universities who were paid for their participation. The participants were divided into three groups ($n = 16$). Each group solved one practice plus nine test antenna placement problems in one of the three view conditions, 2-D, 3-D, or Side-by-Side.

Stimuli

The Antenna Placement Task was authored in Macromedia Director® (Macromedia, 1995). It was displayed on one or two 17-inch color monitors (the Side-by-Side condition used two monitors). Each antenna problem consisted of a different 9- by 7-mile swath of terrain, source and terminal antennas, several enemy units, and a set of antennas to be placed on the map to establish line-of-sight communications (figure 3). The moveable antennas were initially placed in a row along the top of the

screen, and participants could use the mouse to drag the antennas onto the terrain. The number of moveable antennas varied with the difficulty of the problem. The enemy units were placed to create only one viable line-of-site route through the terrain.

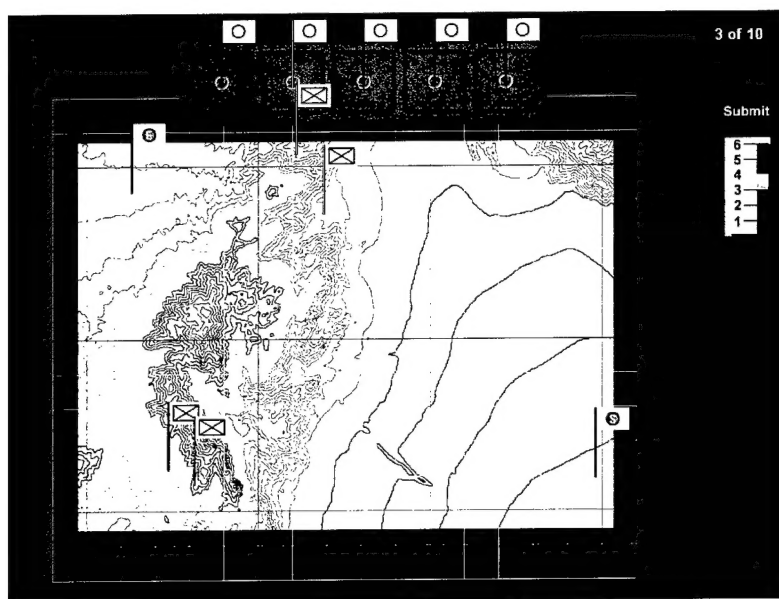
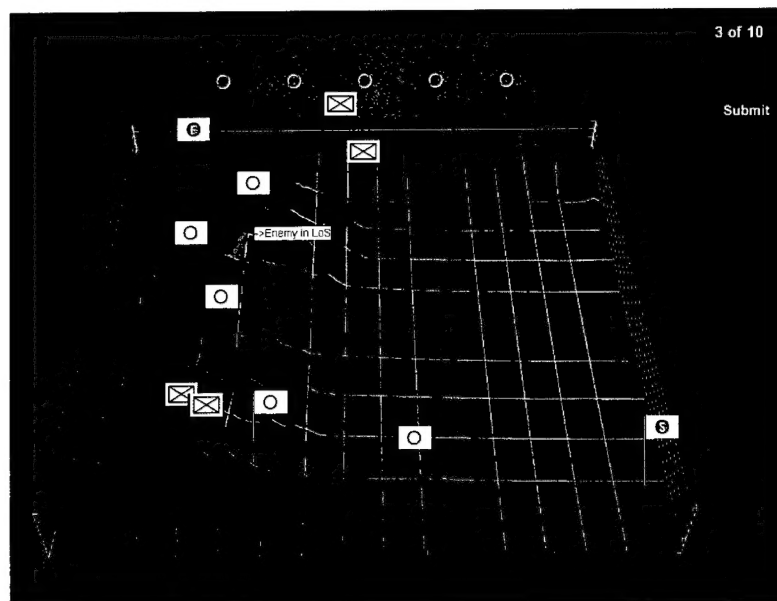


Figure 3. The 3-D view (top) and 2-D view (bottom) in the antenna placement experiment. Flags with a red "X" identify enemy positions. Flags with blue circles identify antennas. The source flag contains an "S" (start) and the terminal flag contains an "F" (finish).

All units were represented as flags, and the exact locations of units were indicated by a green dot at the bottom of each flagpole. In the 3-D view, the locations of units, as shown by the flag pole bottoms, were calculated using a displacement map. When the flags were moved around the display, the flag poles followed the altitude of the terrain as seen from the participant's perspective. As an antenna was moved around the terrain, it was possible for the bottom of its flagpole to move behind a hill and out of view from the participant's perspective. When this situation occurred, the hidden portion of the flagpole turned red. Participants could use this information to place antennas on the far sides of hills.

The terrain views were created from U.S. Geological Survey Digital Elevation models. These models were processed through *Microdem* (Guth, 2000) to create elevation bitmaps. (Altitude was exaggerated on some 3-D views to make the terrain more dramatic.) The 2-D views were topographic maps that were created by drawing iso-altitude contour lines on a white background. Unlike typical topographic maps, which use numbers to indicate altitude, we color-coded the contour lines to indicate altitude. This change was intended to make map interpretation easier. *Microdem* assigned dark blue for the lowest altitude on a map, ran through the chromatic spectrum for intermediate altitudes, and assigned magenta for the highest altitude on a map. Gray grid lines were rendered onto the map to provide scale.

The 3-D views were created by importing elevation bitmaps into *3D Studio Max* (Autodesk, 1999). The camera had a standard 40-degree horizontal field of view and a 50-mm lens. A light source (representing the sun) was placed directly east of the center of the map and at 50 degrees above ground level from the center of the map. The camera was moved to the south of the map so that the entire map was visible while maintaining a 45-degree angle between ground level and the line of sight from the camera to the center of the map. The display was rendered as a ray-traced image with shading, but no shadows. Red and yellow grid lines were rendered onto the surface of the terrain, and a "boxing ring" was placed around the left, right, and back sides of the terrain to provide an altitude scale. The six "ropes" of the boxing ring correspond to the six colors of the contour lines on the 2-D view.

For the 2-D and 3-D conditions, problems were displayed on a 17-inch color monitor. For the Side-by-Side condition, problems were displayed on a pair of 17-inch color monitors placed side by side. The 2-D view appeared on the left. To help participants move between the views and find corresponding points, the moveable antennas were yoked so that they moved equivalently and simultaneously in both views. Using either view, participants could use the mouse to easily move and place antennas.

Procedure

We instructed the participants to create a line-of-sight antenna chain as quickly as possible. They had to satisfy three rules to create a chain: (1) consecutive antennas in the chain must be able to see one another, (2) antennas must be no more than seven grid units apart, and (3) no antennas must be visible to any enemy units. We told participants that the antennas and enemy units were fairly tall, roughly half the height of one rung on the boxing ring in a 3-D view or half the height of a color change in a topographic map. Consequently, antennas would have to be placed behind a substantial terrain feature to remain out of sight.

To avoid undue frustration, we allowed participants to check their developing solutions in two ways. After an antenna was placed, a right click on the mouse would evaluate that antenna for violations of the rules. Text feedback described the nature of any violations. For example, in the top

of figure 3, an antenna was placed within line of sight of an enemy unit. Antennas could be moved and evaluated repeatedly. Once all antennas were placed on a view, the entire solution could be graded by clicking on the "submit" button. The computer would check for a continuous line-of-sight chain of antennas in addition to the three rules. Again, text feedback described violations of any antenna placement rules. Additionally, purple lines would appear to indicate valid line of sights between antennas. Participants were taught to use this information to find gaps in the antenna chain and to find additional antennas that they could use to fill a line-of-sight gap. There were no penalties for checking solutions, and participants were encouraged to use both methods of feedback as often as necessary.

At the beginning of the experiment, participants were provided three strategies for solving the problems because we were interested in the views rather than antenna communication problem solving. The strategies were summarized to the participants as follows:

The first strategy is to start by looking around and deciding on your best route. You may want to go up and around the map, down and around, or straight through the middle. If there is a big canyon, you can follow it to remain out of sight of the enemy.

The second strategy is to follow the bottoms of canyons to remain out of sight of the enemy. It is sometimes necessary to hug one side of a canyon or stay near the very bottom to remain out of the enemy's line of sight. However, remember that you also have to place antennas within line of sight of each other.

The third strategy is to hop along hilltops because those give you a wide view from one antenna to another. However, look out for the enemy's line of sight. Again, first find a promising route. Then, remember that canyons and hillsides are good ways to keep a chain of antennas out of sight of the enemy.

We told participants in the Side-by-Side condition that they could use whichever view worked best at each point during problem solving, but that the 3-D view might be best for choosing a route, and the 2-D view might be best for fine-tuned placement of antennas. We provided this information because our goal was to measure any benefit from having both views visible. We wanted the participants to use the views in the way we believed would be most effective from the beginning of the experiment, rather than developing a strategy for using the views as they progressed through the task.

The first antenna problem was performed with guidance and commentary from the experimenter and was later discarded from the analysis. The participants solved the remaining nine problems without assistance. As a final method to reduce frustration, problems timed-out after 4 minutes and the screen advanced to the next antenna placement problem.

RESULTS AND DISCUSSION

Time-outs after 4 minutes were few, but no inconsequential. Participants averaged 2.6 time-outs out of nine possible test problems, with some problems having more time-outs than others. If a problem timed-out, its solution time was recorded as 240 seconds (4 minutes).

Because of the unexpected number of time-outs, response times for the different conditions did not vary as much as they might have otherwise. Nonetheless, response times to complete each antenna problem were significantly different by condition ($F(2, 405) = 8.8, p < .0002$) and between

each condition.² As figure 4 shows, the 3-D view produced the slowest solution times, and the Side-by-Side display produced the fastest solution times. The number of time-outs recorded was also significantly different by condition ($F(2, 405) = 12.9, p < .0001$). Post hoc analysis³ found that both the 2-D view condition and the Side-by-Side condition produced significantly fewer time-outs than the 3-D view condition.

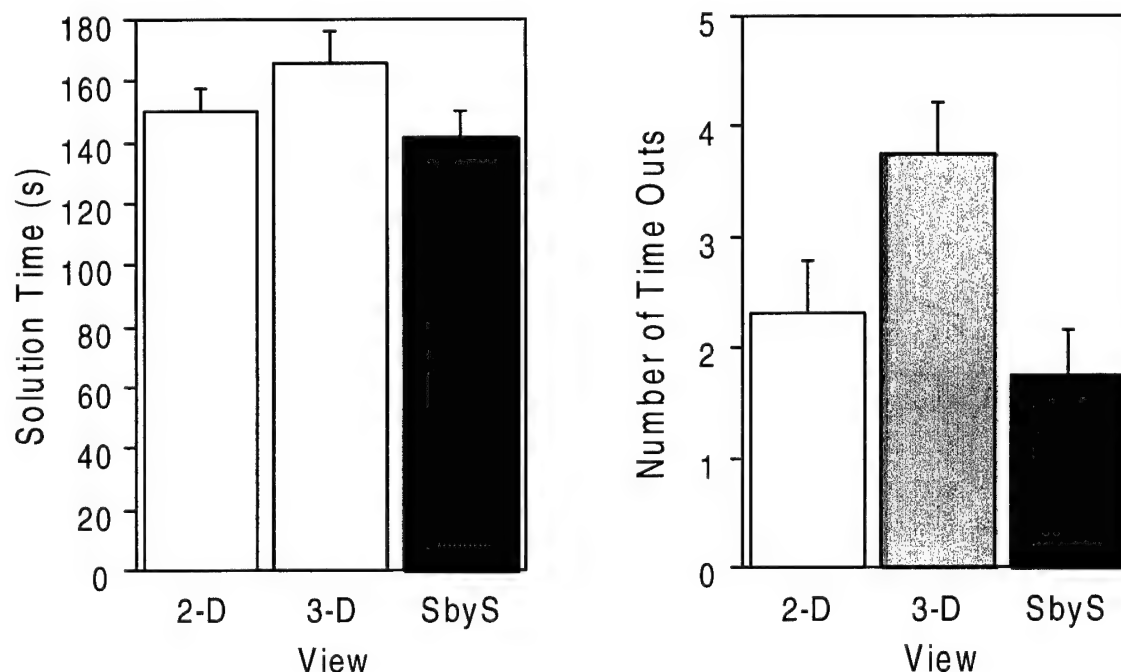


Figure 4. Mean latency in seconds (left) to solve an antenna placement problem and mean number (right) of times (out of nine problems) that a participant ran out of time.

The superior performance of the 2-D views was somewhat surprising. Our previous experiment with gross line-of-sight judgments found that 3-D views were superior to a top-down 2-D view (St. John, Oonk, and Cowen, 2000). Our current finding may reflect the precision required to place two objects in line of sight on uneven terrain. In our previous task, proficiency in determining if two objects were in line of sight depended on understanding only the general layout of the terrain. If hills lay between two points, then the view from one point to the other would be obscured. The general sense of the terrain was helped by the integrated perception of objects and background found in 3-D views. Figure 5 shows an example. The enemy unit and Antenna One lie on opposite sides of a mountain range. It is evident from the 3-D view that the mountain range occludes the line of sight between them.

² Post hoc Fisher's probabilistic least significant difference (PLSD) tests ($p < .05$).

³ Post hoc Fisher's PLSD tests ($p < .05$).

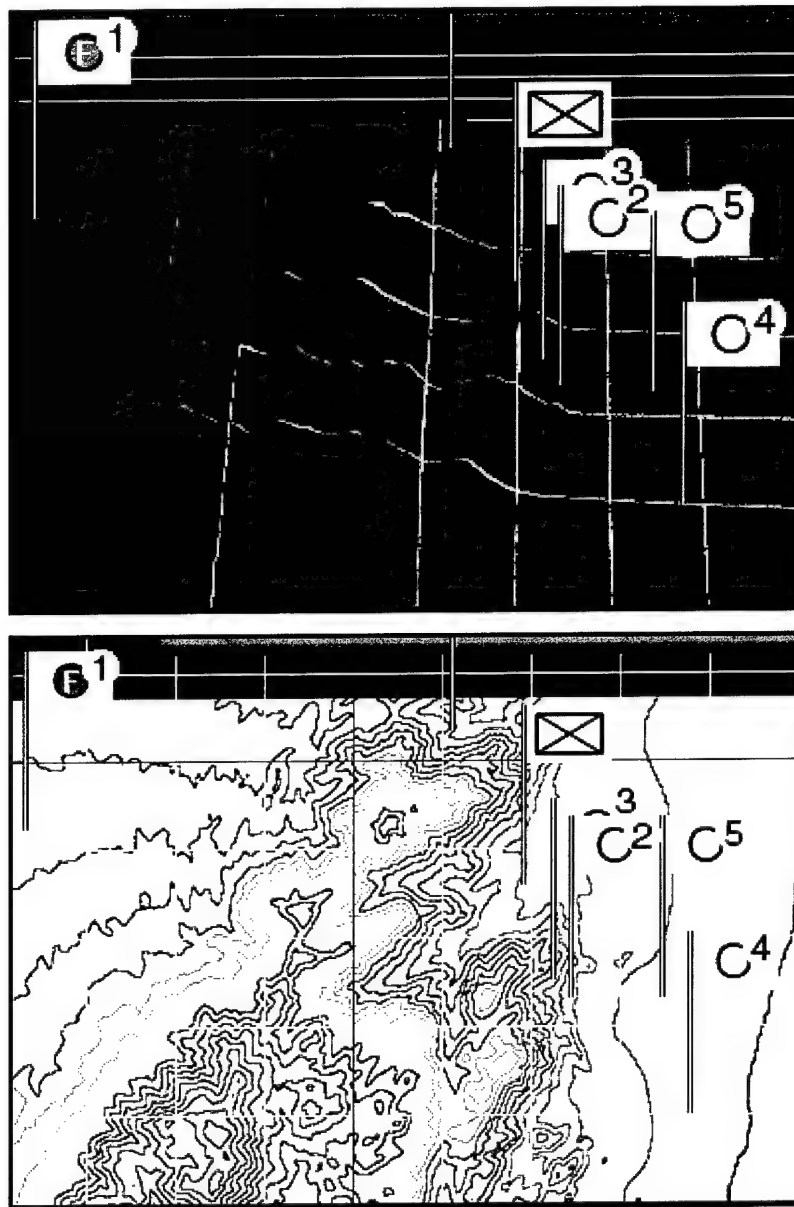


Figure 5. Gross line-of-sight judgments in a 3-D view (top) and precise line-of-sight judgments in a 2-D view (bottom). The line-of-sight judgment from the enemy unit to Antenna 1 requires little precision, but judging the lines of sight from the enemy unit to Antennas 2 through 5 require substantial precision.

In contrast, the line-of-sight judgments in the Antenna Placement Task required far more precision. Placing antennas clearly in view of each other exposes them to being viewed by the enemy, and placing them clearly out of view of the enemy hides them from each other. Instead, antennas must border hills, just remaining within line of sight of each other and out of sight of the enemy units. This precise understanding of the terrain was helped by the faithful representation of distances and elevations provided by 2-D views. In the 3-D view in figure 5, Antennas 2 and 3 appear to be over a ridge and out of view of the enemy unit. However, the 2-D view shows that Antenna 3 is located near

the top of the ridge, and is visible to the enemy unit (recall that antennas are tall). Antenna 2, however, is low enough to break the line of sight to the enemy unit. Similarly, Antennas 4 and 5 in the 3-D view appear to lie behind a small ridge and out of sight of the enemy, but inspecting the scene in 2-D reveals that the ridge does not obstruct the line of sight between the enemy and Antenna 5. The 2-D view also shows that Antenna 4 lies just behind the ridge and out of sight.

However, the performance with 2-D views was not superior to the performance with the Side-by-Side views. Consequently, 3-D views are valuable when combined with 2-D views. From post-experiment interviews, participants in the Side-by-Side condition indicated that the 3-D views were useful in the interpretation of the 2-D topographic views. We also observed that participants tended to concentrate mostly on the 2-D view, but looked at the 3-D view around the beginning of each problem, possibly to find canyons and hills that could be used to build a route through the terrain. In Experiment 2, we investigated this possibility by focusing on the initial phase of the Antenna Placement Task, where a promising route should be first identified.

EXPERIMENT 2: PICK-A-PATH

The initial phase of solving the Antenna Placement Task is to search for a promising route through the general layout of the terrain. This task involves finding canyons and other terrain features where antennas can be hidden from enemy view. Because 3-D views help in understanding the shape and layout of terrain (St. John and Cowen, 1999; St. John, Oonk, and Cowen, 2000), 3-D views should help in finding promising antenna placement routes. We created the Pick-a-Path task to test this hypothesis. We showed participants the Antenna Placement Task problems from Experiment 1 with three potential routes identified. Their task was to choose the most promising route; they did not have to solve the puzzle. We hypothesized that the 3-D perspective view of the terrain would be superior to the top-down 2-D view for picking the most promising path.

METHOD

Participants

The participants were 24 students from local universities who were paid for their participation and who had not participated in Experiment 1.

Stimuli

There were 25 trials presented in either 2-D or 3-D (figure 6). Each trial consisted of terrain containing a start flag and a finish flag. Three potential line-of-sight paths were drawn in purple. One path followed canyons and other terrain and, therefore, held promise for creating a chain of antennas. Another path clearly fell within view of at least one enemy unit. The path route clearly traversed the high point of a hill or mountain range. The antennas on that route would very likely be visible. A group of four people who were very experienced with the Antenna Placement Task (including three of the authors) unanimously agreed on the most promising path for each trial.

Procedure

The participants were all initially trained to perform the actual Antenna Placement Task from Experiment 1 so that they would have a good sense of the nature of a "promising" path. This training began with the verbal instructions for the Antenna Placement Task, followed by having the participants solve three problems with the experimenter's help. Next, we instructed the participants on the Pick-a-Path task. We asked them to evaluate the three paths, and choose the one that held the most promise. Half of the participants saw 2-D views and half saw 3-D views. Rolling over a path with a mouse highlighted the path, and clicking on a highlighted path recorded a response for the trial. We told the participants whether their answers were correct, and showed them a running average of their performance.

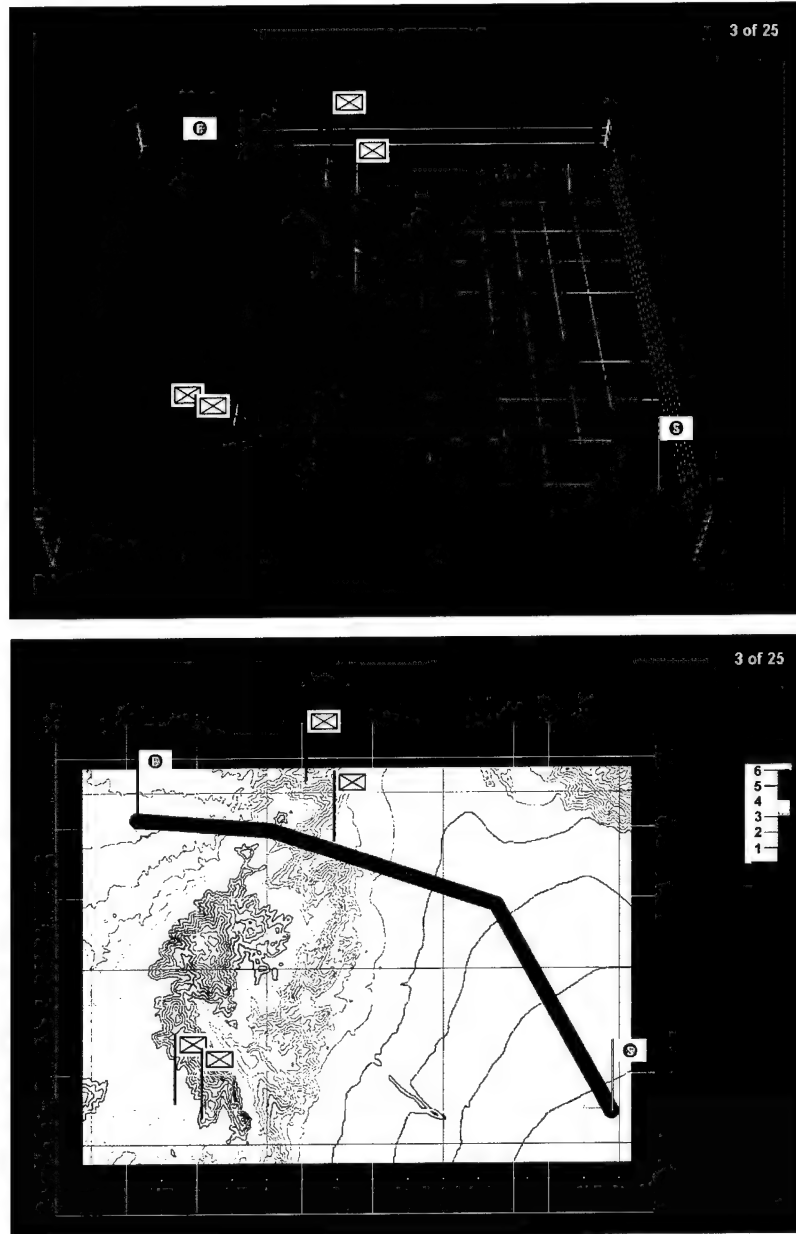


Figure 6. The 3-D (top) and the 2-D (bottom) views in the Pick-A-Path Task. Three potential paths were drawn in purple. Participants controlled the highlighting of paths (the lower path on the 3-D view and upper path on the 2-D view).

RESULTS AND DISCUSSION

Overall, participants picked the correct path on 74 percent of the trials (figure 7). Proportion-correct scores did not vary significantly by view. However, response times on correctly answered trials were significantly different between the views ($F(1, 22) = 10.2, p < .005$). Participants viewing the 3-D display were more than 50 percent faster than those viewing the 2-D display (figure 7), which supports our hypothesis that 3-D views are better for initially planning a route. Participants

were able to more quickly understand the general layout and shape of the terrain with the 3-D perspective view.

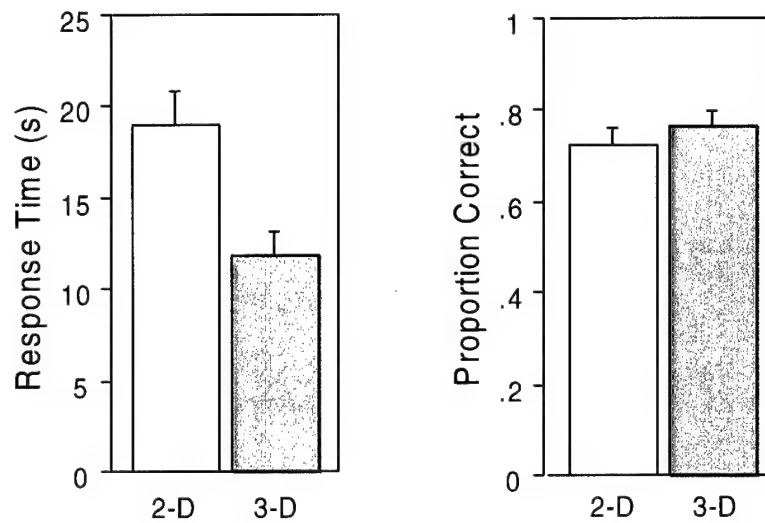


Figure 7. Mean latency in seconds (left) and mean proportion correct (right) for picking the most promising path across the terrain.

GENERAL DISCUSSION

We found that the ability to select a path on a terrain map depends not only on the viewing angle (e.g., 2-D, 3-D), but also on how precise the route must be. Initial path planning benefited from a 3-D view while the actual routing of the antennas benefited from a 2-D view. The 3-D view was better able to convey terrain shapes and the 2-D view was better able to convey where two objects needed to be placed to solve the tactical problem. Our finding, which suggests using 3-D for initial path planning and 2-D for object placement, supports our display design paradigm called "Orient and Operate." Our concept is that users should orient to a scene using a 3-D perspective view, and then operate on the objects in the scene using a 2-D view.

We found that participants performed the best when provided both 2-D and 3-D views, which also supports the "Orient and Operate" concept. However, the effect was of small magnitude, and we believe that more improvement is possible. Placing views side by side may not be sufficient for creating an effective suite of displays. The user must re-orient to the scene to move from one view to the other. Methods are needed to improve the correspondences between objects in the views that alleviate the effects of re-orientation. The concept of visual momentum (Woods, 1984) may offer ideas, such as natural and artificial landmarks, for improving the correspondence. Investigation of these and other concepts is in progress.

Our tactical routing experiments extended our program of research on how to improve perception of displayed objects to a more complex and applied operational domain. In this domain, we found considerable support for our basic distinction for using 3-D perspective views for shape understanding and for using 2-D views to judge relative position of objects. Using this framework, we are currently building several "Orient and Operate" advanced display concepts that we will insert into a real-world military application.

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14. ABSTRACT Consoles for military and civilian occupations such as air warfare, command and control, air traffic control, piloting, and meteorological forecasting will be capable of displaying three-dimensional (3-D) perspective views. The question is when and how to use 3-D views effectively. This report discusses the results of two experiments where participants placed objects on a terrain map in 3-D or two-dimensions (2-D). In these experiments, we showed participants a terrain map that contained two fixed antennas (a source and terminal), several enemy unit locations, and a set of antennas to be placed on the map to establish line-of-sight communications. The task was to create a chain of antennas across the map to connect the source and terminal antennas. The antennas had to be within line of sight of each other while remaining concealed from the enemy units. We found the following: (1) antenna placement was performed better with a 2-D view than a 3-D view, (2) antenna placement was performed best when participants were provided with both a 2-D and 3-D view, and (3) initial planning of the antenna route was performed better with a 3-D view than a 2-D view.												
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